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PHOTOGRAPHIC STUDY OF PROPELLANT OUTFLOW FROM A CYLINDRICAL TANK DURING WEIGHTLESSNESS

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SUMMARY

The NASA Lewis Research Center is currently conducting a study of the problems associated with the behavior of rocket engine propellants stored in space vehicle tanks while exposed to weightlessness. As part of this overall study, a photographic investigation was conducted to examine the behavior of the liquid-vapor interface during pumping or outflow from a cylindrical tank in a zero-gravity environment.

The results indicate that significant distortion of the interface occurs as the outflow velocity is increased. The effects of diffusing the incoming pressurizing gas and baffling the tank outlet were to minimize the interface distortion and to delay vapor blowthrough.

Author

INTRODUCTION

As a part of an overall study to determine the behavior of rocket engine propellants stored in space vehicle tanks while exposed to weightlessness (zero gravity), the NASA Lewis Research Center is currently conducting a study to determine the effect on the liquid-vapor interface of pumping or outflow disturbances in a zero-gravity environment.

A large portion of the zero-gravity research work that has been conducted to date has been given to the determination of means of assuring that liquid is located over the pump inlet prior to engine starting (refs. 1 to 4). Comparatively little work has been devoted, however, to a study of the effect of propellant outflow on the behavior of the liquid-vapor interface. There is an almost complete absence of literature reporting either analytical or experimental studies of the phenomena.

The purpose of this report is to present the results of a photographic study investigating factors that affect the behavior of the liquid-vapor interface during propellant outflow under weightless conditions. The study, conducted in a 2.3-second drop tower, was limited to one test liquid (ethanol) and to a cylindrical tank.

APPARATUS AND PROCEDURE

Test Facility

The drop tower is the 21-foot-square, 100-foot-tall building shown schematically in figure 1. The experiment package was suspended from the top of the tower and dropped to the first floor, where it was decelerated in a 7-foot-deep bed of sand. The drop distance was 85 feet and the weightless time 2.3 seconds. Air drag was maintained below 10^{-5} g by allowing the experiment to free fall inside an air drag shield.

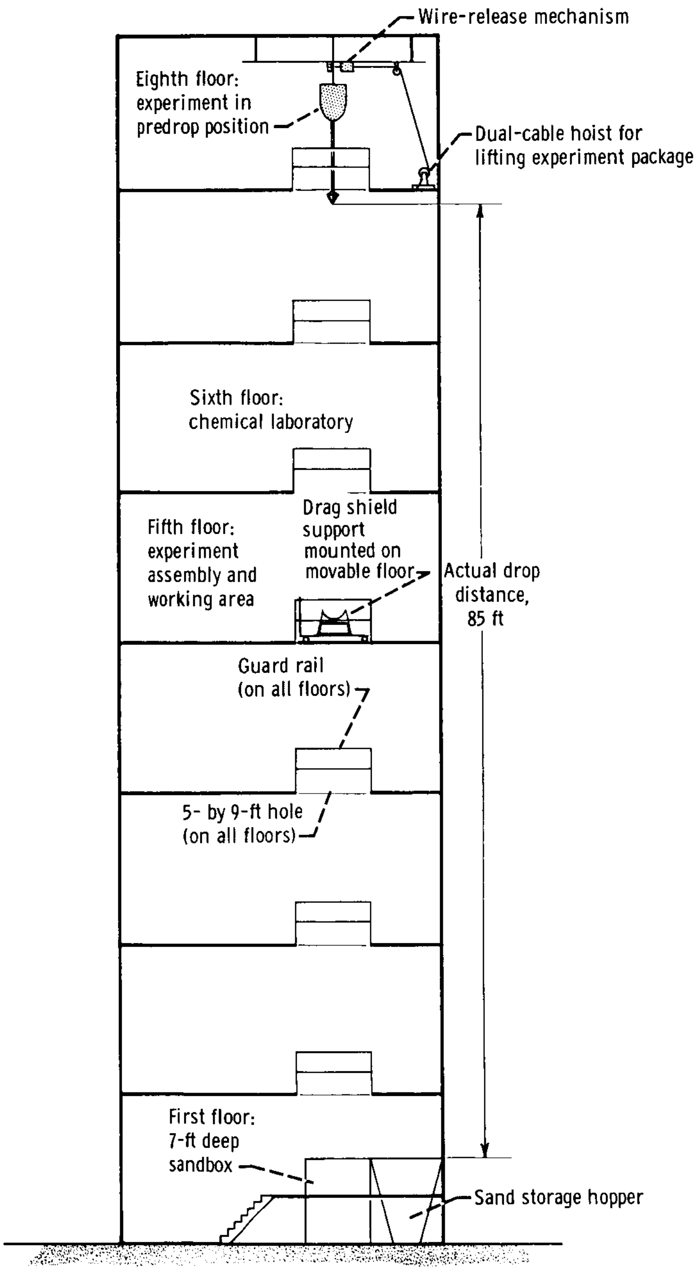


Figure 1. - Schematic view of 100-foot drop tower.

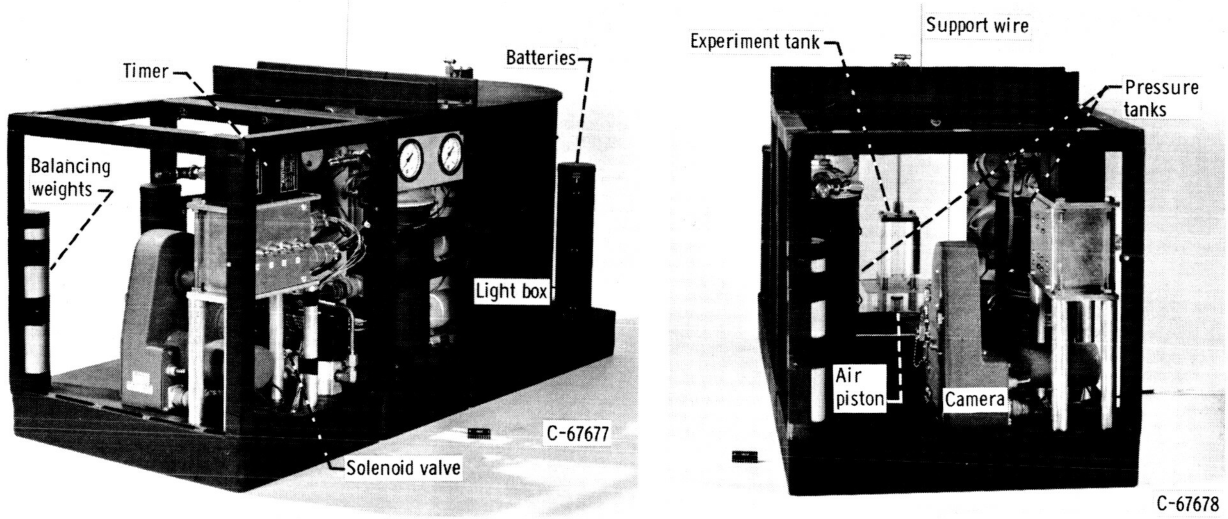
Experiment Tanks and Test Liquid

The model tank used in this investigation was a cylinder machined from cast acrylic rod with an inside diameter D of 4 centimeters and a length of 8 centimeters (2D). The flat top and bottom of the tank were fabricated from stainless steel, with O-rings inserted to sustain pressure in the tank. The tank inlet and outlet were located on the centerline of the tank, and each had an inside diameter of 0.4 centimeter (0.1 D). The outlet was sharp edged and had a length of 2.0 centimeters (0.5 D).

The purity-certified liquid used in this investigation was 200-proof ethanol with a small amount of methylene blue dye added to improve the photographic quality of the data film. The addition of the dye had no measurable effect on the physical properties of the ethanol.

Experiment Package

The experiment tank used in this study was mounted in the experiment package (fig. 2) and suitably illuminated to permit



(a) View showing components.

(b) View of experiment tank mounted in light box.

Figure 2. - Experiment package.

high-speed photography of the interface behavior during free fall with a 16-millimeter motion-picture camera. All electrical power required for the experimental package was carried on the package and consisted of rechargeable nickel-cadmium cells. A solenoid valve controlled a small air piston that held the experiment tank outlet closed during predrop preparations.

Air pressure, supplied to the top of the tank through stainless steel tubing, pumped the liquid from the tank when the air piston was opened. The pressure supply was contained in pressure bottles, which had a volume of 2000 cubic centimeters. The pressure was set with a mercury manometer. Because the pressure tank volume was made large (nominally 30 to 1) with respect to the amount of liquid removed from the model tank, no appreciable pressure decrease resulted while liquid was being pumped from the model tank.

Operating Procedure

Prior to assembling the experiment tank in the light box for test dropping, the tank and other equipment required for filling the tank with ethanol were thoroughly cleaned ultrasonically. The liquid used in the ultrasonic cleaner was distilled water with detergent. The parts were rinsed with distilled water and dried in a warm air dryer.

The experiment tank was assembled in the experiment package and pressure checked for leaks with the air piston at the tank outlet in the closed position. The tank was then filled to a height of three-quarters of the total tank height, and the system pressurized to the desired pressure for pumping the liquid from the tank.

After the camera was loaded with film, the experiment package was balanced about the vertical geometric axis by adding weights where required. The package was then placed in the air drag shield, and the entire assembly hoisted to its predrop position. The assembly was suspended by music wire attached to the experiment package. The music wire was severed, and the air drag shield and experiment package were then in free fall. The solenoid, actuated by the timer, opened the outlet of the experiment tank nominally 0.25 second after the initiation of free fall. The 0.25-second delay in pumping allowed the liquid-vapor interface to assume its zero-gravity configuration. It should be noted that this amount of time is generally not sufficient to ensure the complete absence of oscillatory interface motion. The time was adequate to allow for sufficiently damped interface motion, however, so that after outflow was initiated, the subsequent behavior of the interface was not observed to be influenced by residual transient effects.

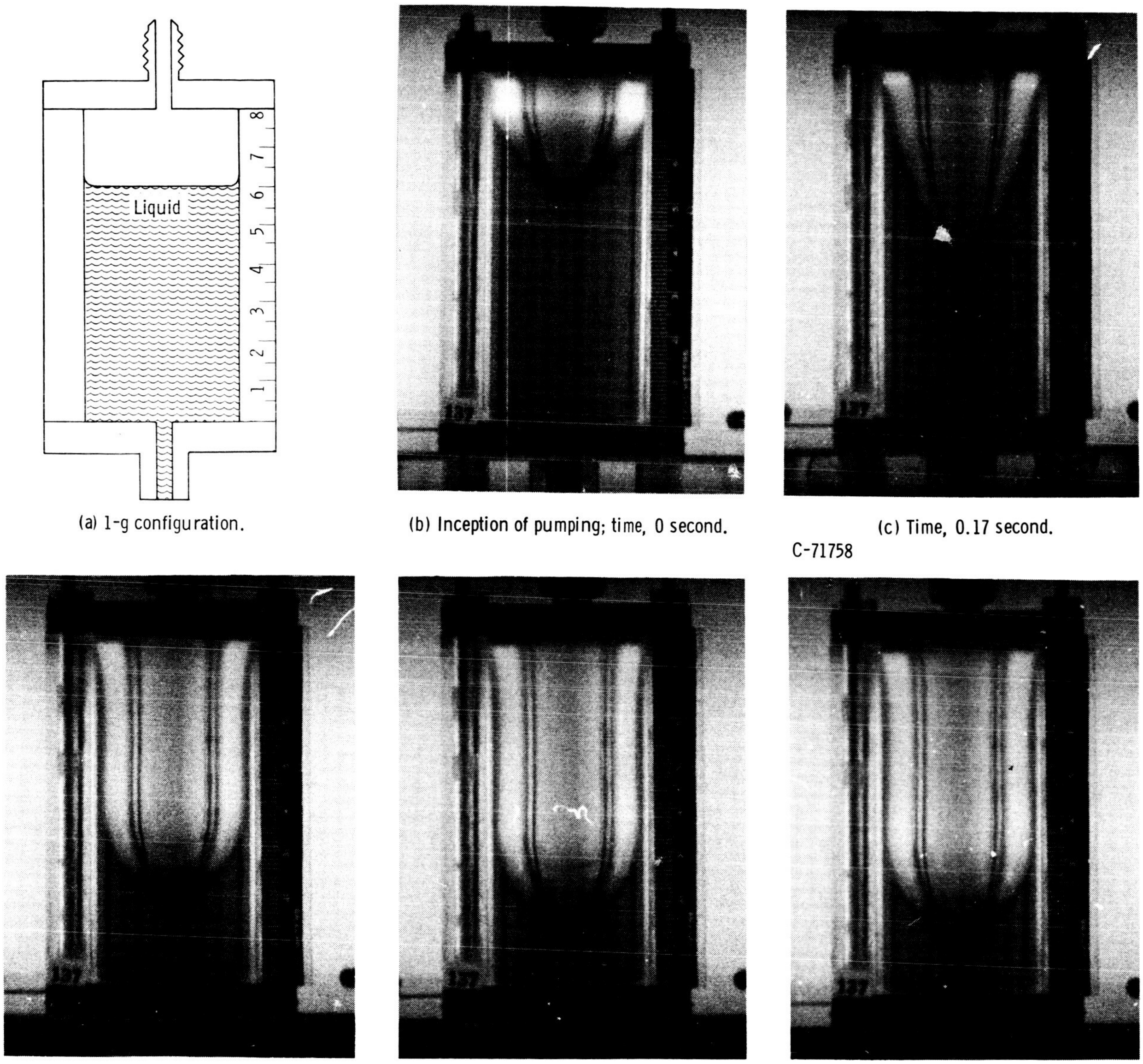
RESULTS AND DISCUSSION

The experimental results of this investigation are presented (figs. 3 to 7) in the form of selected photographs taken from the motion-picture data obtained during each test drop. The behavior of the liquid-vapor interface and vapor blowthrough during outflow in a weightless environment are discussed in relation to the variables of outflow velocity and internal tank geometry. In addition to the photographic data, schematic diagrams are presented in each figure that illustrate the 1-g configuration of the liquid-vapor interface and the geometry of the tank under investigation. The zero-gravity outlet velocity given in each figure was obtained by measuring the change in liquid depth during outflow with time in 1-g calibration tests and then accounting for the loss in pressure due to static head in a zero-gravity environment. A set of typical photographs showing the interface configuration and behavior during outflow at 1 g is presented in figure 8 (p. 10). It should be noted that the liquid-vapor interface remains in essentially the same configuration before and during outflow, that is, no distortion of the interface was observed in the 1-g calibration tests.

Effect of Outlet Velocity

In order to determine the gross effect of outlet velocity on the behavior of the liquid-vapor interface, two tests were conducted. The photographic results obtained at an outlet velocity of 291 centimeters per second are presented in figure 3, and figure 4 presents the results at an outlet velocity of 1408 centimeters per second.

An examination of the photographic results at the relatively low outlet velocity of 291 centimeters per second (fig. 3) reveals that, shortly after outflow begins, the interface becomes conically shaped (fig. 3(c)), and a considerable amount of liquid remains on the tank wall as the interface moves in the direction of the tank outlet. As outflow continues, the center of the interface remains nearly stationary as liquid is removed from the tank wall until the liquid-vapor interface has nearly returned to its zero-gravity equilibrium configuration (fig. 3(d)). The entire interface then progresses toward the tank outlet until the inception of vapor blowthough, as shown in fig-



(a) 1-g configuration.

(b) Inception of pumping; time, 0 second.

(c) Time, 0.17 second.

(d) Time, 0.97 second.

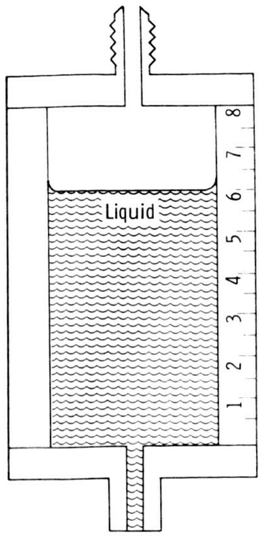
(e) Inception of blowthrough; time, 1.19 seconds.

(f) Vapor blowthrough; time, 1.22 seconds.

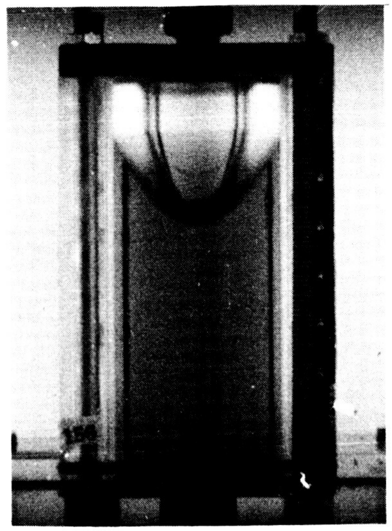
Figure 3. - Interface configuration during outflow from cylindrical tank. Outlet velocity, 291 centimeters per second.

ure 3(e). In figure 3(f), vapor entered the tank outlet 1.22 seconds after outflow began, and the remaining outlet flow is a mixture of liquid and vapor.

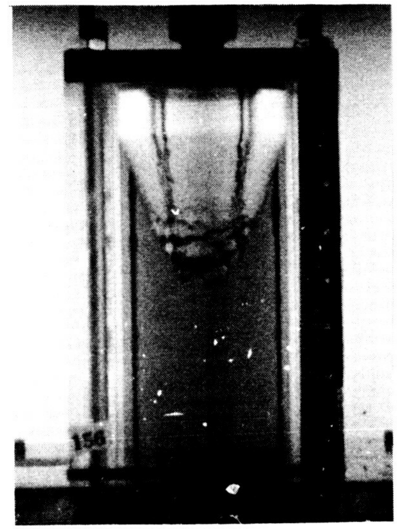
When the outlet velocity was increased to the relatively high value of 1408 centimeters per second, significant distortion of the liquid-vapor interface occurred immediately after outflow began and persisted until vapor blowthrough was observed (0.10 sec after initiation of outflow). This severe interface distortion, as shown in figure 4, resulted in an appreciable amount of liquid remaining on the tank walls when vapor entered the outlet as compared with that observed at the low value of outlet velocity.



(a) 1-g configuration.



(b) Inception of pumping; time, 0 second.



(c) Time, 0.03 second.

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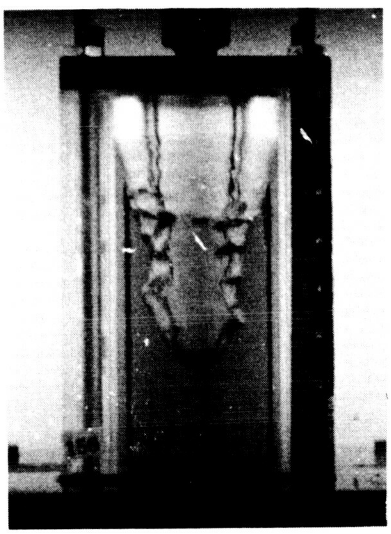
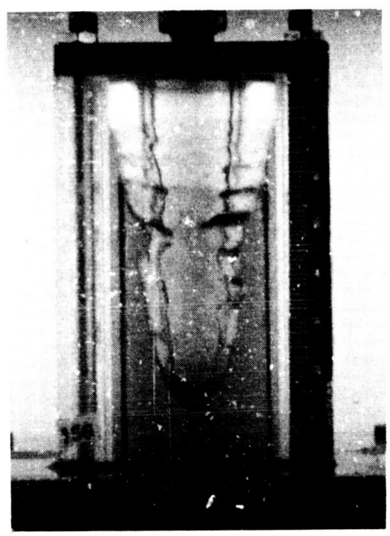
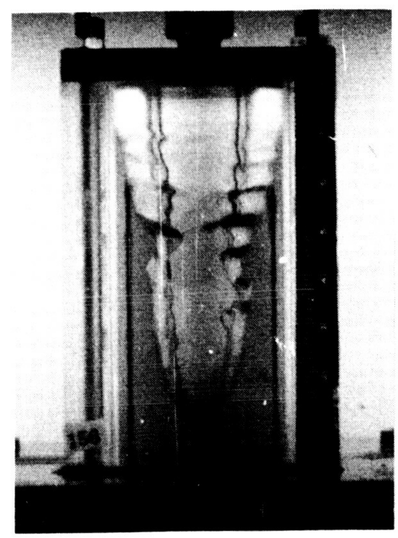


(d) Time, 0.07 second.



(e) Inception of blowthrough; time 0.09 second.



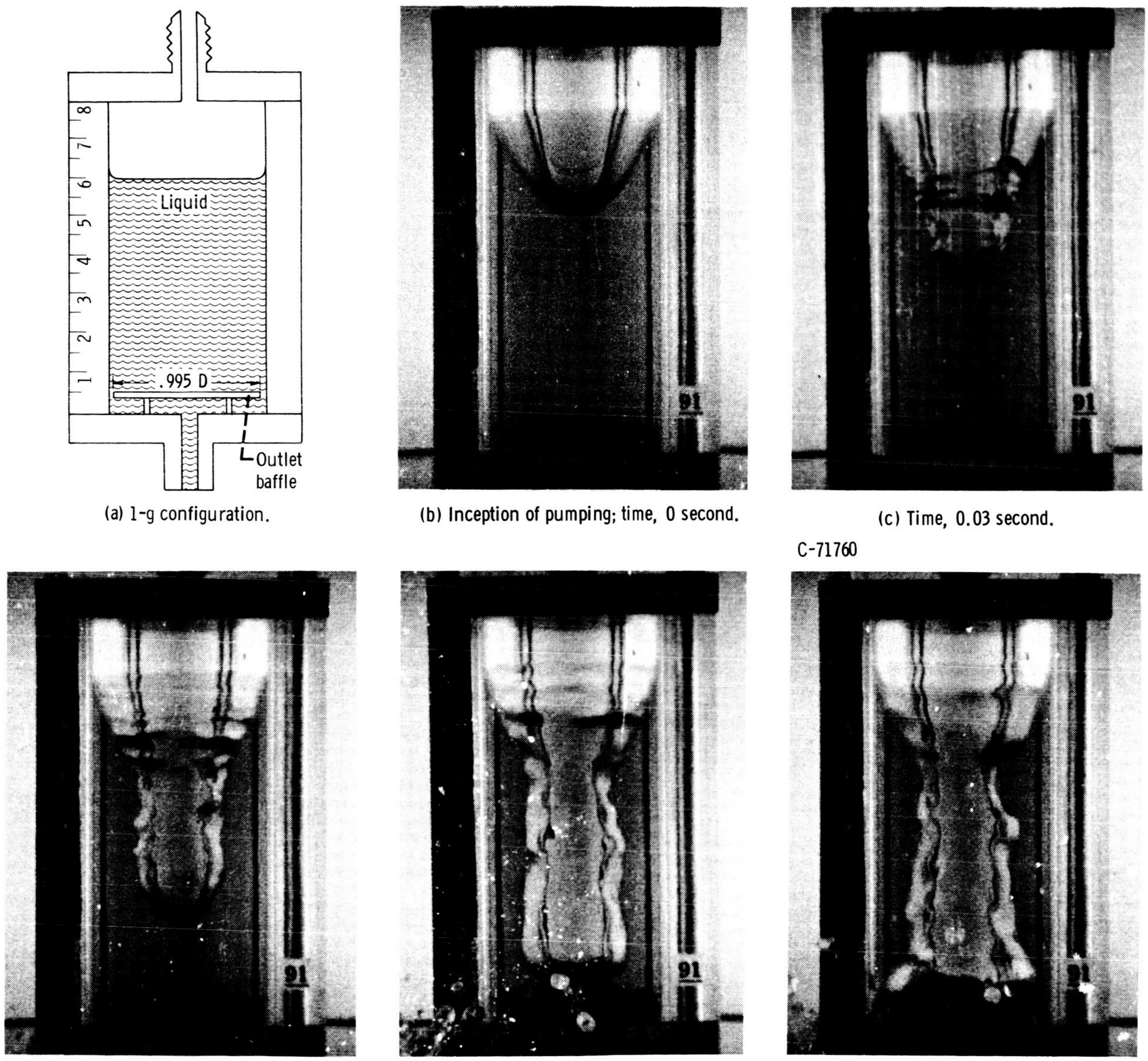
(f) Vapor blow through; time, 0.10 second.

Figure 4. - Interface configuration during outflow from cylindrical tank. Outlet velocity, 1408 centimeters per second.

Effect of Baffle at Tank Outlet

The results of propellant outflow at an outlet velocity of 1330 centimeters per second from a cylindrical tank with a circular baffle mounted 3 millimeters above the tank outlet are presented in figure 5. The baffle had an area of 99 percent of the cross-sectional tank area, which resulted in an annular flow area for the liquid that was equal to the area of the tank outlet (1 percent of tank area).

As seen in the photographs, the liquid-vapor interface became distorted as



(a) 1-g configuration.

(b) Inception of pumping; time, 0 second.

(c) Time, 0.03 second.

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(d) Time, 0.06 second.

(e) Time, 0.11 second.

(f) Vapor blowthrough; time, 0.15 second.

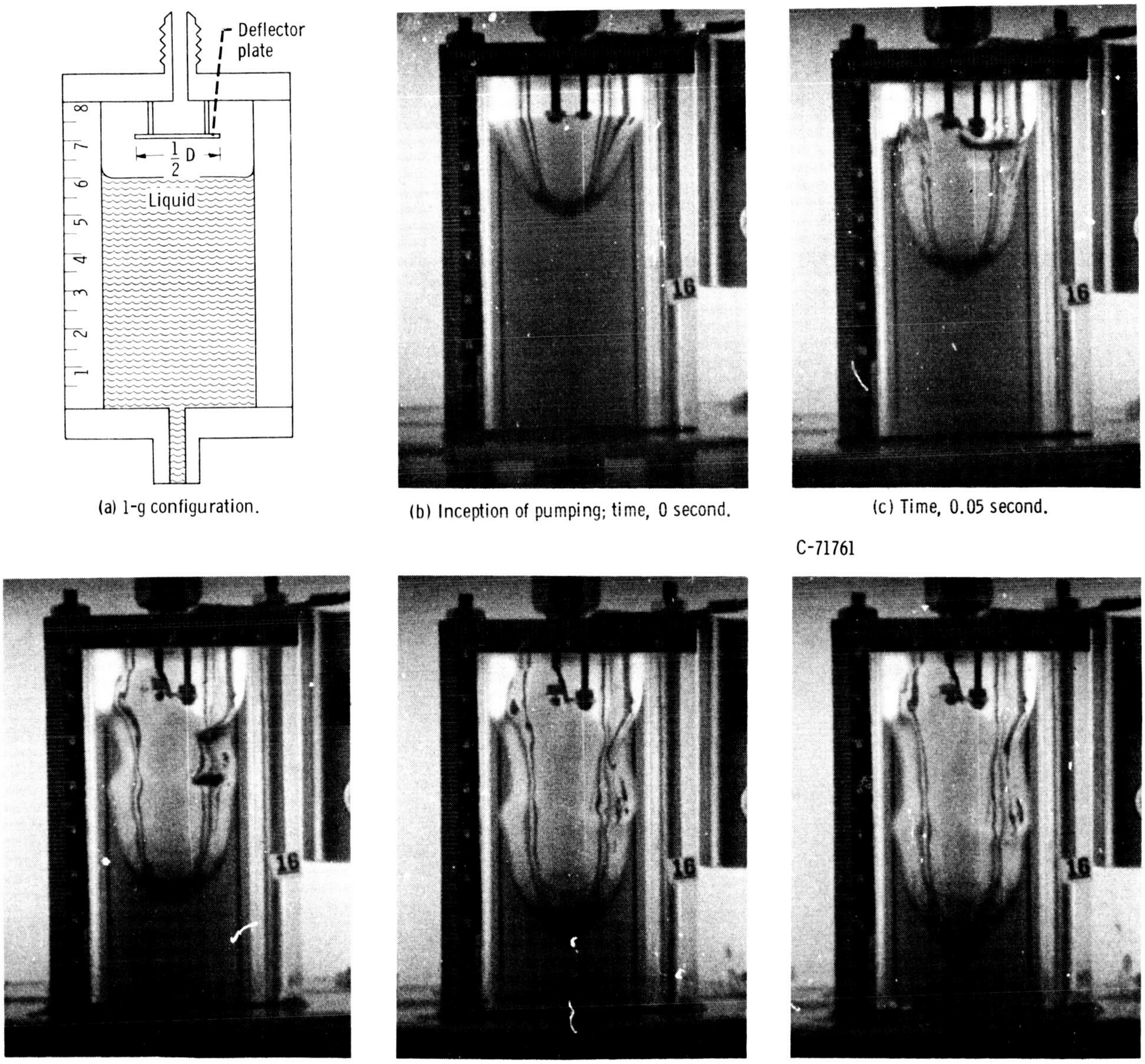
Figure 5. - Interface configuration during outflow from cylindrical tank with baffled outlet. Outlet volocity, 1330 centimeters per second.

outflow progressed in much the same manner as was observed in the unbaffled tank at nearly the same outlet velocity (see fig. 4). As the interface approached the baffle, liquid was withdrawn from above the baffle and along the tank wall near the tank bottom. The liquid expulsion time of 0.15 second was an improvement over the 0.10 second obtained in the unbaffled tank at nearly the same outflow velocity. Although the outlet baffle did not appear to reduce the liquid-vapor interface distortion at this outflow velocity, it did retard vapor blowthrough at the tank outlet.

Effect of Deflector at Gas Inlet

The results of propellant outflow at 1427 centimeters per second from a tank with a deflector plate to prevent the incoming air from impinging directly on the interface are shown in figure 6. The deflector plate was circular with a diameter of one-half the tank diameter. It was mounted one-fourth tank diameter down from the top of the tank with three small screws.

After initiation of pumping, the liquid-vapor interface moves down the tank very nearly in its zero-gravity equilibrium configuration (fig. 6), as was



(a) 1-g configuration.

(b) Inception of pumping; time, 0 second.

(c) Time, 0.05 second.

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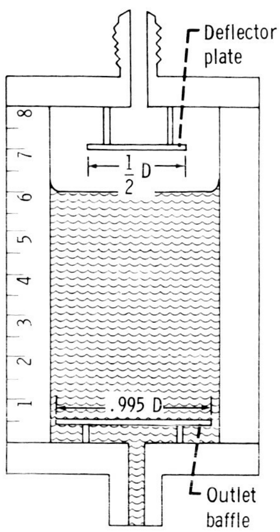
(d) Time, 0.12 second.

(e) Inception of blowthrough; time, 0.15 second.

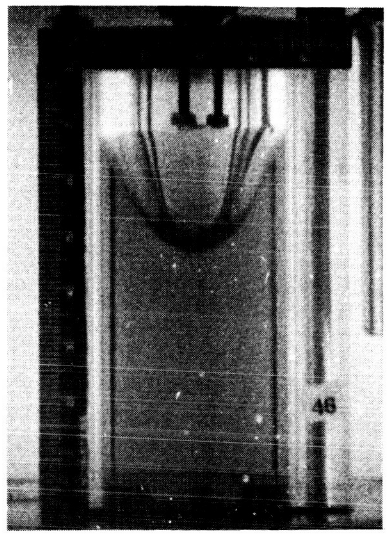
(f) Vapor blowthrough; time, 0.17 second.

Figure 6. - Interface configuration during outflow from cylindrical tank with baffled inlet. Outlet velocity, 1425 centimeters per second.

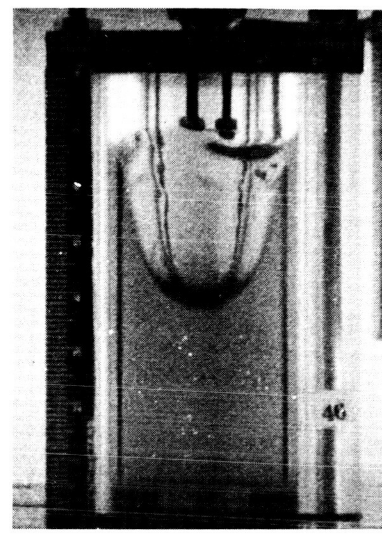
previously observed for the case shown in figure 3, where the outlet velocity was significantly lower (291 cm/sec). When these results are compared with those for the tank that had no deflector plate and a high outlet velocity (fig. 4), it is apparent that the deflector plate significantly reduced the interface distortion and resulted in a liquid expulsion time of 0.17 second. It also is noted that the depth of liquid directly over the tank outlet at vapor blowthrough is not affected to any appreciable extent.



(a) 1-g configuration.



(b) Inception of pumping; time, 0 second.



(c) Time, 0.04 second.

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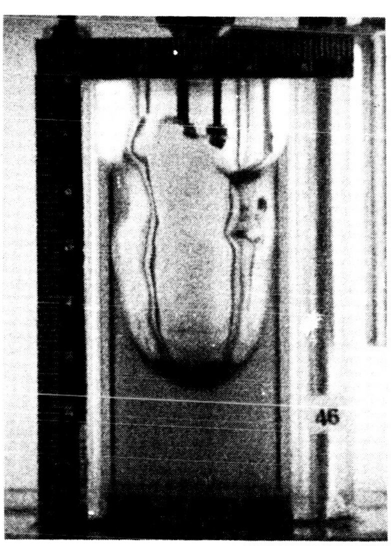
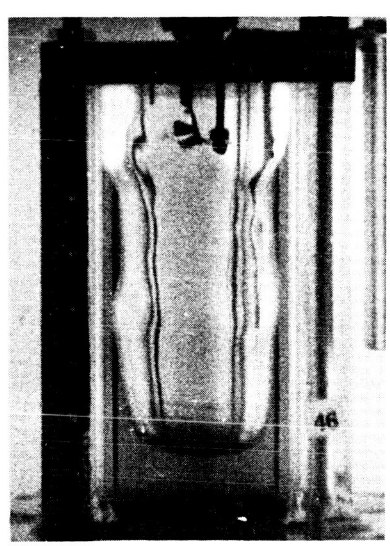
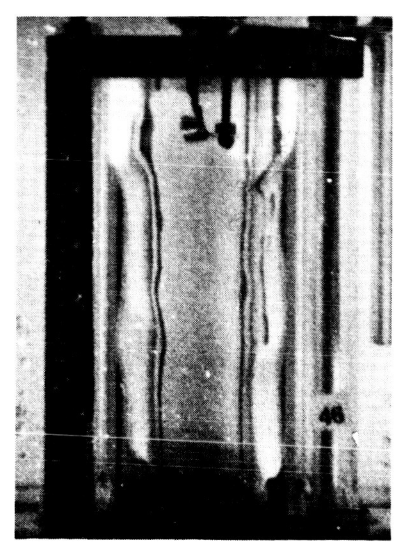


(d) Time, 0.12 second.



(e) Time, 0.21 second.



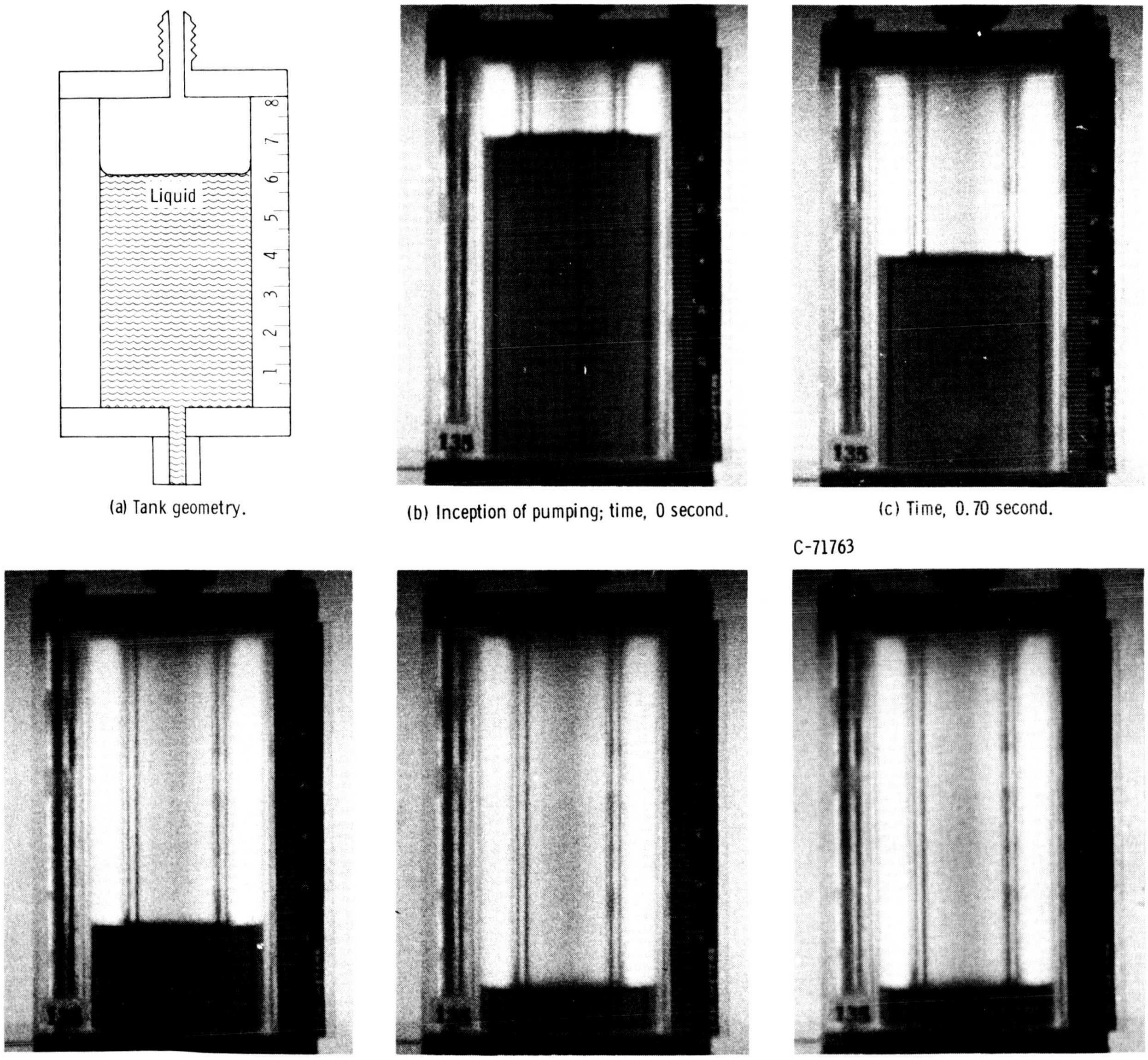
(f) Vapor blowthrougn; time, 0.25 second.

Figure 7. - Interface configuration during outflow from cylindrical tank with baffled inlet and baffled outlet. Outlet velocity, 1348 centimeters per second.

Combined Effect of Inlet Deflector and Outlet Baffle

The results of propellant outflow, at an outlet velocity of 1348 centimeters per second, from a cylindrical tank equipped with an outlet baffle and an inlet air deflector are presented in figure 7. The baffle and deflector are identical to those previously discussed.

Pumping begins after the liquid-vapor interface has assumed its zero-gravity configuration, and, as pumping progresses, the interface nearly maintains this configuration with some liquid on the tank wall. This interface



(a) Tank geometry.

(b) Inception of pumping; time, 0 second.

(c) Time, 0.70 second.

(d) Time, 1.45 seconds.

(e) Inception of blowthrough; time, 1.96 seconds.

(f) Vapor blowthrough; time, 1.98 seconds.

Figure 8. - Typical interface configuration during outflow from cylindrical tank at 1-g.

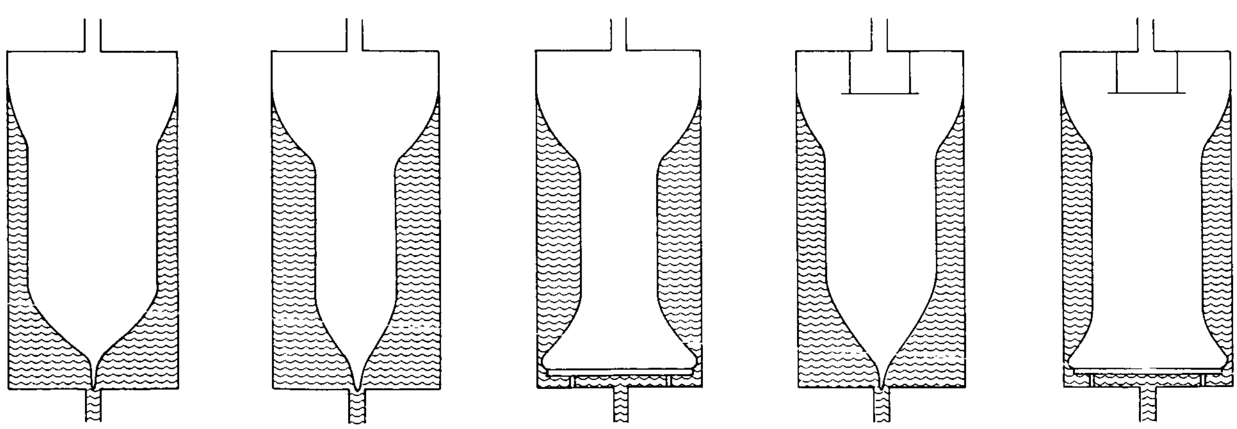
shape is similar to that shown in figure 6, where only the deflector plate was in the tank.

As the interface approaches the outlet baffle, vapor blowthrough is retarded in the same manner as previously noted in figure 5. The liquid expulsion time was 0.25 second for this tank geometry. The conclusion from this test is that the inlet deflector and the outlet baffle, when combined in a tank, produce the same results as each accomplished by itself. By combining the two, the advantages of each one were incorporated in the same tank, and the result was minimum interface distortion and the longest liquid-expulsion time before blowthrough.

CONCLUDING REMARKS

This investigation presents qualitative results of the effects of outlet velocity, outlet baffling, and inlet gas diffusion on the liquid-vapor interface configuration during outflow from a cylindrical tank. The results are summarized in figure 9, where sketches of representative interface configurations are presented for each tank geometry investigated. Figure 9 also shows the outlet velocity and the amount of liquid expelled prior to vapor blowthrough. The amount of liquid expelled is a relative measure of the effect of outlet velocity and internal tank baffling on the liquid-vapor interface while the liquid is pumped from the tank during weightlessness. The inlet deflector plate and the outlet baffle employed in this investigation were not considered to be optimum designs, but were intended to provide an insight into the effects that baffles may have in affecting the liquid-vapor interface configuration during propellant outflow from a tank.

The results of this investigation indicate the liquid-vapor interface configuration during outflow can be significantly affected by the magnitude of the



(a) Outlet velocity, 291 centimeters per second; expelled liquid, 47 cubic centimeters.

(b) Outlet velocity, 1408 centimeters per second; expelled liquid, 18.7 cubic centimeters.

(c) Outlet velocity, 1330 centimeters per second; expelled liquid, 26 cubic centimeters.

(d) Outlet velocity, 1427 centimeters per second; expelled liquid, 32 cubic centimeters.

(e) Outlet velocity, 1348 centimeters per second; expelled liquid, 45 cubic centimeters.

Figure 9. - Typical interface configuration during outflow from cylindrical tank in weightlessness.

outlet velocity and the distribution of the incoming pressurization gas. Increasing the outlet velocity results in an increased distortion of the interface and causes a reduction in the amount of propellant expelled from the tank (see figs. 9(a) and (b)). When a deflector plate was provided to distribute the inlet air flow more uniformly, the interface distortion was considerably reduced in comparison with the tank with no inlet deflector plate (see figs. 9(b) and (d)). Both of these factors, low outlet velocity and an inlet air deflector plate, served the purpose of holding the interface distortion to a minimum. The result of installing the outlet baffle was to prolong the time during which liquid was flowing into the outlet. The baffle proved to be an effective means of delaying vapor blowthrough (see figs. 9(b) and (c)).

When the inlet air deflector and the outlet baffle were utilized at the same time, the advantages of each were realized, and the result was minimum interface distortion and maximum liquid expulsion (see fig. 9(e)).

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, September 22, 1964

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